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Physical properties of blazar jets from VLBI observations

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Abstract. Relativistic jets, formed in the vicinity of central supermassive black holes in AGN, show ample evidence connecting them to physical conditions in the accretion disc and broad-line region. The jets are responsible for a large fraction of non-thermal continuum emission (particularly during powerful flares), which makes understanding their physics an important aspect of studies of blazars characterised by profound flaring activity arising from extremely compact regions. Imaging and polarimetry of radio emission on milliarcsecond scales provided by very long baseline interferometry (VLBI) offers a range of possibilities for studying ultra-compact regions in relativistic jets and relating them to main manifestations of the blazar activity in AGN. Simultaneous monitoring of optical/high energy variability and evolution of parsec-scale radio structures yields arguably the most detailed picture of the relation between acceleration and propagation of relativistic flows and non-thermal continuum generation in blazars. Opacity effects provide a measure of magnetic field strength on scales down to ~ 1000 gravitational radii and trace the distribution of broad-line emitting material. Correlations observed between parsec-scale radio emission and optical and gamma-ray continuum indicate that a significant fraction of non-thermal continuum may be produced (particularly during flares) in extended regions of relativistic jet at distances up to 10 parsecs from the central engine. Combined with studies of jet component ejections and X-ray variability, these correlations also suggest that time delays, nuclear opacity, and jet acceleration may have a pronounced effect on the observed broad-band variability and instantaneous spectral energy distribution (SED). These effects will be reviewed below and discussed in the context of deriving accurate and self-consistent models for central regions of blazars.

1. Introduction

In the current astrophysical paradigm for active galactic nuclei (AGN), each constituent of an AGN contributes to a specific domain in the broad-band spectral energy distribution (Ghisellini & Tavecchio 2009). Variability of continuum flux in AGN, signalling the activity of the central engine, is detected throughout the entire electromagnetic spectrum, on time-scales from days to years. Substantial progress achieved during the past decade in studies of active galactic nuclei (see Lobanov & Zensus 2006 for a review of recent results) has brought an increasingly wider recognition of the ubiquity of relativistic outflows (jets) in AGN (Falcke 2001, Zensus 1997) and in blazars in particular.

Understanding the physics of blazars jets has acquired a particular importance after the launch of *Fermi Gamma-Ray Space Telescope*, as the compact, relativistic flows contribute strongly to the broad-band continuum – a fact that is still somewhat overlooked in physical models describing high-energy emission from AGN.

Emission properties, dynamics, and evolution of an extragalactic jet are intimately connected to the characteristics of the supermassive black hole, accretion disk and broad-line region in the nucleus of the host galaxy (Lobanov 2008). The jet continuum emission is dominated by non-thermal synchrotron and inverse-Compton radiation (Unwin et al. 1997). The synchrotron mechanism plays a more prominent role in the radio domain, and the properties of the emitting material can be assessed using the turnover point in the synchrotron spectrum (Lobanov 1998b, Lobanov & Zensus 1999), synchrotron self-absorption (Lobanov 1998a), and free-free absorption in the ambient plasma (Walker et al. 2000, Kadler et al. 2004).

There is growing evidence for relativistic flows contributing substantially to generation of non-thermal continuum in the optical (Arshakian et al. 2010, León-Tavares et al. 2010, Jorstad et al. 2010), X-ray (Unwin et al. 1997, D'Arcangelo et al. 2007, Marscher et al. 2008), Soldi et al. 2008, Chatterjee et al. 2009), γ-ray (Otterbein et al. 1998, Jorstad et al. 2010, Marscher et al. 2010, Savolainen et al. 2010, Schinzel et al. 2010) and TeV (Piner & Edwards 2004, Charlot et al. 2006, Acciari et al. 2009) domains. Accurate spatial localisation of production sites of variable non-thermal continuum emission in AGN is therefore instrumental for understanding the mechanism for release and transport of energy in active galaxies.

In the radio regime, very long baseline interferometry (VLBI) enables direct imaging of spatial scales comparable the gravitational radius, $R_{\rm g} = G\,M_{\rm bh}/c^2$, of the central black hole in AGN using ground VLBI observations at 86 GHz and higher (*cf.,* GMVA[1] observations; Krichbaum et al. 2008) and space VLBI observations at centimetre wavelengths (Takahashi et al. 2004). Such high-resolution radio observations also access directly the regions where the jets are formed (Junor et al. 1999), and trace their evolution and interaction with the nuclear environment (Lobanov 2007, 2008 and Middelberg & Bach

[1] Global Millimeter VLBI Array; http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm

2008). Evolution of compact radio emission from several hundreds of extragalactic relativistic jets is now systematically studied with dedicated monitoring programs and large surveys using very long baseline interferometry (such as the 15 GHz VLBA[2] survey (Kellermann et al. 2004) the MOJAVE[3] survey (Lister & Homan 2005) and a dedicated 22/43/86 GHz VLBA gamma-ray blazar monitoring program at the Boston University[4] (Jorstad et al. 2001). These studies, combined with optical and X-ray studies, yield arguably the most detailed picture of the vicinity of supermassive black holes in AGN (Marscher 2005).

Presented below is a brief (and certainly incomplete) summary of recent results from VLBI studies of compact extragalactic radio sources, outlining the physical properties of relativistic parsec-scale jets and their relation to supermassive black holes, accretion disks and broad-line regions in prominent blazars.

2. Physics of compact jets

Jets in active galaxies are formed in the immediate vicinity of the central black hole (Camenzind 2005), at distances of 10–$10^2\,R_\mathrm{g}$ (Meier 2009). The jets carry away a fraction of the angular momentum and energy stored in the accretion flow (Blandford & Payne 1982, Hujeirat et al. 2003 or corona (in low luminosity AGN; Merloni & Fabian 2002) and in the rotation of the central black hole (Blandford & Znajek 1977, Koide et al. 2002, Komissarov 2005, Semenov et al. 2004).

The production of highly-relativistic outflows requires a large fraction of the energy to be converted to Poynting flux in the very central region (Sikora et al. 2005). The efficiency of this process may depend on the spin of the central black hole (Meier 1999). The collimation of such a jet requires either a large scale poloidal magnetic field threading the disk (Spruit et al. 1997) or a slower and more massive MHD outflow launched at larger disk radii by centrifugal forces (Bogovalov & Tsinganos 2005). The flowing plasma is likely to be dominated by electron-positron pairs (Wardle et al. 1998, Hirotani 2005) although a dynamically significant proton component cannot be completely ruled out at the moment (Celotti & Fabian 1993).

Acceleration or collimation of the flow may be complete within about $10^3\,R_\mathrm{g}$ (Meier et al. 2009) or continue all the way to scales of a few parsecs (Vlahakis & Königl 2004). At distances of $\sim 10^3\,R_\mathrm{g}$, the jets become visible in the radio regime. Recent studies indicate that at 10^3–$10^5\,R_\mathrm{g}$ (≤ 1 pc) the jets are likely to be dominated by pure electromagnetic processes such as Poynting flux (Sikora et al. 2005) or have both MHD (kinetic flux) and electrodynamic components (Meier 2003). At larger scales, the jets are believed to be kinetic flux-dominated. The magnetic field is believed to play an important role in accelerating and collimating extragalactic jets on parsec scales (Vlahakis & Königl 2004). Three distinct regions with different physical mechanisms dominating the observed properties of the jets can be considered: 1) ultra-compact jets (on scales of up to ~ 1 pc) where collimation and acceleration of the flow occurs; 2) parsec-scale flows (~ 10 pc scales) dominated by relativistic shocks and 3) larger-scale jets (~ 100 pc) where plasma instability gradually becomes dominant. This picture may be further complicated by transverse stratification of the flow, with the jet velocity, particle density and magnetic field changing substantially from the jet axis to its outer layers. As a practical result of this stratification, shocks and instabilities may in fact co-exist on all scales in the jets, with instabilities simply remaining undetected in compact flows, owing to limited resolution and dynamic range of VLBI observations.

[2] Very Long Baseline Array of National Radio Astronomy Observatory, USA

[3] http://www.physics.purdue.edu/MOJAVE

[4] http://www.bu.edu/blazars

2.1. Ultra-compact jets

Blazar jets usually feature a bright, compact (often unresolved) "core" and a weaker, extended jet (often also transversely unresolved), with several regions of enhanced emission (traditionally branded "jet components") embedded in the flow and separating from the core at apparently superluminal speeds. The radio core is offset from the true base of the jet, and this "invisible" flow is probably Poynting flux-dominated (Meier 1999, 2003; Sikora et al. 2005).

The radio core has a flat spectrum, expected to result from synchrotron self-absorption in a conically expanding ultra-compact flow (Königl 1981). As a result, the observed position, r_c, of the core depends on the frequency of observation, ν, so that $r_\mathrm{c} \propto \nu^{-1/k_\mathrm{r}}$ (this is so called "core shift" effect). If the core is self-absorbed and in equipartition, the power index $k_\mathrm{r} = 1$ (Blandford & Königl 1979). Recent measurements (Kovalev et al. 2008) have also shown that the frequency dependent core shift increases during flares as expected from the synchrotron self-absorption.

The core shift can be used for determining basic physical properties of the ultra-compact flow and the surrounding absorbing material (Lobanov 1998a). Changes of the core position measured between three or more frequencies can be used for determining the value of k_r and estimating the strength of the magnetic field, B_core, in the nuclear region and the offset, R_core, of the observed core positions from the true base of the jet. The combination of B_core and R_core gives an estimate for the mass of the central black hole $M_\mathrm{bh} \approx 7\times 10^9\,M_\odot\,(B_\mathrm{core}/\mathrm{G})^{1/2}(R_\mathrm{core}/\mathrm{pc})^{3/2}$.

Core shift measurements provide estimates of the total (kinetic + magnetic field) power, the synchrotron luminosity, and the maximum brightness temperature, $T_\mathrm{b,max}$ in the jets can be made. The ratio of particle energy to magnetic field energy can also be estimated, from the derived $T_\mathrm{b,max}$. This enables testing the original Königl model and several of its later modifications (e.g., Hutter & Mufson 1986; Bloom & Marscher 1996). The known distance from

the nucleus to the jet origin can also enable constraining the self-similar jet model (Marscher 1995) and the particle-cascade model (Blandford & Levinson 1995).

Studies of free-free absorption in AGN indicate the presence of dense, ionised circumnuclear material with $T_\mathrm{e} \approx 10^4\,\mathrm{K}$ distributed within a fraction of a parsec of the central nucleus (Lobanov 1998a, Walker et al. 2000). Properties of the circumnuclear material can also be studied using the variability of the power index k_r with frequency. This variability results from pressure and density gradients or absorption in the surrounding medium most likely associated with the broad-line region (BLR). Changes of k_r with frequency, if measured with required precision, can be used to estimate the size, particle density and temperature of the absorbing material surrounding the jets. Estimates of the black hole mass and size of the BLR obtained from the core shift measurements can be compared with the respective estimates obtained from the reverberation mapping and applications of the M_bh–$\sigma_\star$ relation.

The non-thermal continuum radio emission from the jet core does not appear to have strong shocks (Lobanov 1998b), and its evolution and variability can be explained by smooth changes in particle density of the flowing plasma, associated with the nuclear flares in the central engine (Lobanov & Zensus 1999). Compelling evidence exists for acceleration (Vlahakis & Königl 2004, Bach et al. 2005, Lee et al. 2008) and collimation (Junor et al. 1999, Krichbaum et al. 2008) in the ultra-compact flows.

The brightness temperature of the radio emission from the cores reaches the inverse-Compton limit of $\approx 10^{12}\,\mathrm{K}$ (Unwin et al. 1997, Lobanov et al. 2000, Kovalev et al. 2005), while it drops rapidly to the equipartition limit of $\approx 5 \times 10^{10}\,\mathrm{K}$ in the jet components moving downstream from the core (Lähteenmäki et al. 1999, Lobanov et al. 2000, Homan et al. 2006). This supports earlier conclusions that ultra-compact jets are particle-dominated, while the plasma in moving jet components is likely to be close to the equipartition (Unwin et al. 1997, Lobanov 1998a, Hirotani). Combining these calculations with estimates of the jet kinetic power provides strong indications that the relativistic fraction of the outflowing material is most likely represented by the electron-positron plasma (Reynolds et al. 1996, Hirotani et al. 2000, Hirotani 2005).

2.2. Parsec-scale flows: shocks and instabilities

Parsec-scale outflows are characterised by pronounced curvature of trajectories of superluminal components (Kellermann 2004, Lobanov & Zensus 1999), rapid changes of velocity and flux density (Lister et al. 2009) and predominantly transverse magnetic field 2005. Statistical studies of speed and brightness temperature distributions observed in the superluminal features propagating on parsec scales indicate that the jet population has an envelope Lorentz factor of ≈ 30 and an un-beamed luminosity of $\sim 1 \times 10^{25}\,\mathrm{W\,Hz^{-1}}$ (Cohen et al. 2007).

Physical conditions of the jet plasma can be assessed effectively by studying the spectral peak (turnover point) of the synchrotron emission. Mapping the turnover frequency distribution provides a sensitive diagnostic of the plasma (Lobanov 1998b). Obviously, the observed morphology and velocity of these flows are affected substantially by Doppler boosting, aberration, and time delays, which makes uncovering true physical properties a nontrivial task (Gomez et al. 1994, Cohen et al. 2007). As a result, it becomes difficult to distinguish between apparent and true physical accelerations of the moving features (Lister et al. 2009) and making such a distinction often requires a detailed physical modelling of a given jet component (Lobanov & Zensus 1999, Homan et al. 2003). Similarly to stellar jets, rotation of the flow is expected to be important for extragalactic jets (Fendt 1997), but observational evidence remains very limited on this issue.

VLBI studies have demonstrated that relativistic shocks are prominent in jets on parsec scales, which is manifested by strong polarization (Ros et al. 2000) and rapid evolution of the turnover frequency of synchrotron emission (Lobanov et al. 1997, Lobanov & Zensus 1999). Evidence is growing for the presence of stationary features in parsec-scale flows, typically separated by $\sim 1\,\mathrm{pc}$ distance from the jet core (Kellermann et al. 2004, Savolainen et al. 2006, Lister et al. 2009, Arshakian et al. 2010, León-Tavares et al. 2010).

Specific geometric conditions and extremely small viewing angles could lead to formation of stationary features in relativistic flows (Alberdi et al. 2000). However, a more general and physically plausible explanation is offered by standing shocks (for instance, recollimation shocks in an initially over-pressurised outflow; Daly & Marscher 1988, Gómez et al. 1995, Perucho & Martí 2007). Such standing shocks may play a major role in accelerating particles near the base of the jet (Mandal & Chakrabarti 2008, Becker et al. 2008), and could be responsible for the persistent high levels of polarization in blazars (D'Arcangelo et al. 2007, Marscher et al. 2008)). More speculatively, the stationary features in jets could also be the sites of continuum emission release due to conversion from Poynting flux-dominated to kinetic flux-dominated flow.

Complex evolution of the moving shocked regions is revealed in observations (Gomez et al. 2001, Jorstad et al. 2005, Lobanov & Zensus 1999) and numerical simulations (Agudo et al. 2001) of parsec-scale outflows. However, the shocks are shown to dissipate rapidly (Lobanov & Zensus 1999), and shock dominated regions are not likely to extend beyond $\sim 100\,\mathrm{pc}$. Starting from these scales, instabilities (most importantly, Kelvin-Helmholtz instability, *cf.,* Hardee 2000) determine at large the observed structure and dynamics of extragalactic jets (Lobanov et al. 1998, Walker et al. 2001, Lobanov & Zensus 2001, Lobanov et al. 2003, Hardee et al. 2005, Perucho et al. 2006).

The elliptical mode of the instability is responsible for appearance of thread-like features in the jet interior , while overall oscillations of the jet ridge line are caused by the

helical surface mode (Lobanov & Zensus 2001). Successful attempts have been made to represent the observed brightness distribution of radio emission on these scales, using linear perturbation theory of Kelvin-Helmholtz instability (Lobanov & Zensus 2001, Lobanov et al. 2003, Hardee et al. 2005) and a spine-sheath (analogous to the two-fluid) description of relativistic flows (Canvin et al. 2005, Laing & Bridle 2004). Non-linear evolution of the instability (Perucho et al. 2004a, 2004b), stratification of the flow (Perucho et al. 2005), and stabilisation of the flow via magnetic field (Hardee 2007) are important for reproducing the observed properties of jets. At larger scales, the helical surface mode of Kelvin-Helmholtz instability is likely to be one of the most important factor for disrupting and destroying the outflows (Lobanov et al. 2003, 2006, Perucho & Lobanov 2007).

2.3. Structure of the magnetic field

The structure of magnetic field in blazar jets can be assessed with VLBI via linear (e.g., Lister & Homan 2005) and circular polarisation (Homan & Lister 2006) measurements. The ultra-compact jets (VLBI cores) are shown to be typically less than 5 % linearly polarised, with the polarisation angle in BL Lac objects showing a stronger tendency to be aligned with the inner jet direction (Lister & Homan 2005). The low degree of polarisation in the VLBI cores can be caused by a disordered magnetic field (Hughes 2005) or strong Faraday de-polarisation (Zavala & Taylor 2004), or result from the "beam de-polarisation" if the magnetic field in the cores is structured on scales much smaller than the resolution of the VLBI experiments.

The fractional linear polarisation in moving jet components grows with increasing distance from the core (Lister & Homan 2005), and the position angle of the polarisation vector is again better aligned with the jet direction in the BL Lac objects. At the same time, the linearly polarised emission in transversely resolved flows displays both strong rotation of the polarisation angle near the core and remarkable edge brightening (e.g., Ros et al. 2000), with the polarisation vectors tending to be perpendicular to the jet direction. This indicates overall complexity and likely stratification of the magnetic field in the jets, with the internal part ("spine") of the flow being dominated by a helical magnetic field further compressed by relativistic shocks, while the external, slower moving layers ("sheath") of the flow could be dominated by a longitudinal magnetic field. This conclusion is in a good agreement with the turnover frequency distribution (Lobanov et al. 1997), internal structure (Lobanov & Zensus 2001), and transverse velocity stratification in the jets (Perucho et al. 2006). Here again, the effect that the flow, and magnetic field, rotation (due to residual angular momentum inherited from the initial disk-to-jet coupling) remains difficult to assess. Presence of a strong toroidal or helical magnetic field either in the spine or in the sheath has also been suggested from observations of Faraday rotation gradients across the flow (Asada et al. 2002, Zavala & Taylor 2005, Attridge et al. 2005, Gomez et al. 2008).

Circular polarisation has been detected in a number of AGN jets (Homan & Lister 2006), with a typical level of polarisation of $\leq$0.5 %. The circular polarisation can be either intrinsic to the synchrotron emission (Legg & Westfold 1968, implying the presence of a strong relativistic proton component) or result from scintillations (Macquart & Melrose 2000), relativistic effects in dispersive plasma (Broderick & Blandford 2002) or Faraday conversion of linearly polarised synchrotron emission from electron-positron plasma (Jones & O'Dell 1977). The observed properties of circularly polarised emission in blazar jets support the last mechanism for its formation (Wardle et al. 1998, Homan & Lister 2006, Homan et al. 2009).

The strength of the magnetic field in blazar jets is typically assessed by combining multi-band measurements (Unwin et al. 1997), by deriving information about the peak in the synchrotron spectrum (Marscher 1983, Lobanov et al. 1997, Lobanov 1998b, Savolainen et al. 2008, Sokolovsky et al. 2010), or by using the opacity due to synchrotron self-absorption (Lobanov 1998a). In most objects, values around 1 G are obtained for the VLBI cores and lower magnetic field is measured in the jets, all falling well in agreement with magnetic field generation being ultimately processes in the magnetised accretion disk (Field & Rogers 1993).

2.4. Periodic changes of the structure

Structural changes are abound on milliarcsecond scales in the blazar jets, enhanced and magnified by small viewing angles and relativistic effects. In addition to extreme curvature observed in the jet ridge line of some objects (e.g., Polatidis et al. 1995), the position angle of the inner jet (as traced by jet components nearest to the core) changes substantially both as a function of observing frequency (Savolainen et al. 2006, Agudo et al. 2007) and in time (Mutel & Denn 2005, Lobanov & Roland 2005).

The frequency dependent changes are most likely caused by the opacity and spectral index gradients in the flow. The temporal variations of the position angle can result from precession and rotation of the flow (Camenzind et al. 1992) as well as from the pattern motion of Kelvin-Helmholtz instability (Hardee 2003, Hardee et al. 2005), in which case the motion should also be evident in long-term evolution of the ridge line of a flow (e.g., Krichbaum et al. 2001).

Variations of the jet position angle, as well as the observed morphology of parsec-scale jets and trajectories of superluminal features propagating in the jets, are often described in terms of a helical geometry (Steffen et al. 1), with helicity supposed to be arising from some periodic process in the nucleus. Jet precession, both in single and binary black hole systems, have been commonly sought to be responsible for the observed helicity on parsec scales. However, as the observed periods of the posi-

tion angle changes (and, similarly, periods inferred from the component trajectories and oscillations of the jet ridge lines) are typically within a range of a few years, the precession-based models face severe difficulties (Lobanov & Roland 2005) as they require either allowing for extremely small ($\leq 10^4\,R_\mathrm{g}$) orbital separations in supermassive binary black holes or adopting an assumption that the jet direction responds exclusively to changes in the innermost parts of the accretion disk and it is decoupled from the spin of the central black hole. In view of these difficulties, rotation of the flow and pattern motion of the instability seem to be more viable alternatives. The precession of the flows, evident on kiloparsec-scales (Gower et al. 1982, Hardee et al. 1994) acts on much longer timescales (typically $\geq 10^4$ yr), typically of several hundred years and longer, and thus should only be visible in long-term changes of the position angle of the entire milliarcsecond-scale jet (Lobanov & Roland 2005).

3. Emission from blazar jets

VLBI observations enable tracing both temporal and spatial changes in radio emission from blazar jets, offering a unique opportunity for connecting these changes to properties of the blazar emission observed in other wavelength domains and even localising spatially the dominant components in the broad-band emission. Emission from jets may also contribute substantially to the broad-band SED (Yuan et al. 2002), alongside with the canonical contributions from the accretion disk and hot material in the vicinity of the central black hole. VLBI observations help here enormously by providing an accurate measure of radio emission produced in these regions and excluding contributions from kiloparsec-scale jets and lobes of radio sources.

3.1. Parsec-scale radio emission

Parsec-scale radio emission is variable on timescales from decades (e.g., O'Dea et al. 1984, Asada et al. 2006) to hours (Savolainen & Kovalev 2008), with the longest timescales most likely related to large-scale changes in the nuclear region feeding the black hole, and the shortest timescales resulting from interstellar scintillations. The variability on hour-to-day timescales may also be related to "quasar QPO" type of variations recently observed in the soft X-ray band (Gierlínski et al. 2008), remembering that if variability periods scale with the black hole mass, this would correspond to canonical QPO seen in X-ray binaries at frequencies around 100 Hz.

On intermediate timescales (months-to-years), most of variable radio emission is believed to be associated with flares in the VLBI cores (Lobanov & Zensus 1999) and shock evolution of plasma propagating downstream (Hughes et al. 1985, Marscher & Gear 1985, Marscher 1990). The radio flares last, on average, for 2.5 years (at a wavelength of about 1 cm; Hovatta et al. 2008), and in many objects they are repeated quasi-periodically (Hovatta et al. 2007). The flares are firmly associated with ejections of new jet components (Valtaoja et al. 1999, Lobanov & Zensus 1999, Marscher et al. 2002, Chatterjee et al. 2009), but the release of non-thermal continuum emission may not necessarily be restricted to the vicinity of the black hole or even the radio core (Arshakian et al. 2010, Leon-Tavares et al. 2010, Schinzel et al. 2010). Detailed evolution of a flaring emission is best determined through variations of its turnover peak (Otterbein et al. 1998, Fromm et al. 2010) and can be further constrained using observed kinematic properties of an emitting region (Lobanov & Zensus 1999).

Quasi-periodic variability of the radio emission from the ultra-compact jets is most likely related to instabilities and non-stationary processes in the accretion disks around central black holes in AGN (Igumenschev & Abramowicz 1999, Lobanov & Roland 2005. Alternative explanations involve binary black hole systems in which flares are caused by passages of the secondary through the accretion disk around the primary Ivanov et al. 1998, Lehto & Valtonen 1996. Similarly to the attempts of using binary black holes to explain short-term morphological changes, these models require very tight binary systems, with orbits of the secondary lying well within $10^4\,R_\mathrm{g}$ of the primary, which poses inevitable problems for maintaining an accretion disk around the primary (for massive secondaries; Lobanov 2008) or rapid alignment of the secondary with the plane of the accretion disk (for small secondaries; Ivanov et al. 1999).

3.2. Blazar jets and broad-band continuum

Relativistic flows are prominent emitters in all bands of the electromagnetic spectrum, generating optical and X-ray emission even on kiloparsec scales (Schwartz et al. 2000, Marshall et al. 2002, Siemiginovska et al. 2002, Sambruna et al. 2008) and at TeV energies (Acciari et al. 2010). The jet plasma is believed to emit via synchrotron emission in the radio to soft X-ray range and via inverse Compton emission in the hard X-ray to TeV range (Acciari et al. 2010, Marscher et al. 2010). Contested is, however, the primary source of the seed photons for the inverse Compton part of the radiation. These could be the synchrotron photons themselves (synchrotron self Compton mechanism, SSC) or photons from an external radiation field located, for instance, in the accretion disc emission, X-ray corona, the broad-line region, the infrared emitting torus and the cosmic background radiation (Ghisellini & Tavecchio 2009).

Results from the first year of the *Fermi*/LAT operations have enabled most detailed studies of the connection between relativistic flows and γ-ray production in blazars. Early statistical comparisons of the properties of γ-ray emission and compact radio jets in blazars indicate unequivocally that they are closely related (Pushkarev et al. 2009, Savolainen et al. 2010). Several of the γ-ray flares detected with *Fermi*/LAT can be associated with

emission from accelerated plasma cloud embedded in the jets (Marscher et al 2010, Schinzel et al. 2010), although detailed localisation of the γ-ray emitting sites remain elusive, clearly calling for continuation of extensive, co-ordinated *Fermi*/LAT and VLBI campaigns.

There is now growing evidence for the broad-band continuum (and its flaring components in particular) to be produced at multiple locations in AGN (Arshakian et al. 2010), with the emission in different bands dominated by contributions from spatially different regions (Leon-Tavares 2010). These findings put an additional strain on single-zone models commonly used for fitting the broad-band SED in AGN. The situation with the quiescent (and slowly variable) component of the γ-ray emission is also puzzling, with indications that it may be produced in the region of the jet extending up to $\sim$10 pc (Schinzel et al. 2010).

These results give a compelling indication that formation of jet components may correspond to the strongest nuclear events, while some of them may not survive a passage through a standing shock (Leon-Tavares et al. 2010). The source of the continuum emission is localised not only in the accretion disk (at the extreme vicinity of the black hole) but also in the entire acceleration zone of the jet, with strong flares happening both near the central black hole and at a standing shock in the jet. Clearly, a more general and systematic study of relation between the radio, optical and X-ray emission in blazars is strongly justified, and co-ordinated VLBI–*Fermi*/LAT campaigns would one of the prime methods for such studies.

4. Outlook

More than thirty years after their appearance on the scientific scene, blazars remain one of the focal points of extragalactic astrophysics. High-resolution radio observations of blazars provide essential information about structure, kinematics and emission of relativistic flows in these objects on scales inaccessible to direct imaging in other bands. This information turns out to be arguably an indispensable tool for constructing viable physical models capable of explaining the blazar phenomenon and its spectacular observational manifestations.

There are still a number of unanswered questions about the jets themselves and their relations to the broad-band emission produced in blazars. Extragalactic jets are an excellent laboratory for studying physics of relativistic outflows and probing conditions in the central regions of active galaxies. Recent studies of extragalactic jets show that they are formed in the immediate vicinity of central black holes in galaxies and carry away a substantial fraction of the angular momentum and energy stored in the accretion flow and rotation of the black hole. The jets are most likely collimated and accelerated by electromagnetic fields. Relativistic shocks are present in the flows on small scales, but dissipate on scales of decaparsecs. Plasma instabilities dominate the flows on larger scales. Convincing observational evidence exists, connecting ejections of material into the flow with instabilities in the inner accretion disks.

In the coming years, new breakthroughs should be coming in studies of relativistic jets and blazars, enriched by *Fermi*/LAT results and by an effective use of the VLBI potential for studies of blazars. There are several potential focal points for these studies.

In particular, the jet composition remains an open issue, in particular with regard to the role of relativistic protons in high-energy emission production in extreme vicinity of the central black holes (while it seems that pair plasma is chiefly responsible for the emission from parsec-scale jets).

Accurate spatial localisation of the sites of high-energy continuum production will play a crucial role for modelling the broad-band SED of blazars and understanding their physical nature in general. To this end, variability of the high-energy continuum emission is best related to structural and radiative changes in parsec-scale radio emission resolved by VLBI observations.

Last but not least, the continued observational quest for reaching ever closer to the regions where the relativistic flows are formed will bring new answers not only about the physical nature of relativistic flows, but also about the physical properties of black holes and their connection to major manifestations of nuclear activity in galaxies. This would be particular important for studies of the γ-ray and TeV emission from blazars, as this emission has all chances to come from the immediate vicinity of the central black holes in galaxies. Combination of high-energy observations with VLBI extensive monitoring at centimetre wavelengths and focused, specific VLBI programs at millimetre wavelengths certainly has a quality of the tool of choice for such studies.

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